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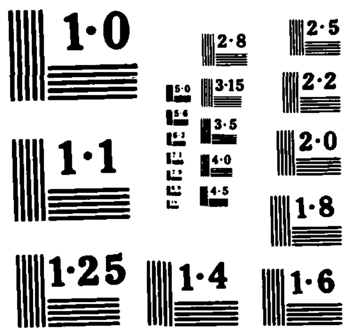

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AD-A155 443

Cerenkov Maser and
Cerenkov Laser Devices

FINAL REPORT

for DAAG29-83-K-0018

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The principle goal of the work supported by this contract was the exploration and development of the Cerenkov Masers. ~~These devices~~ were operated over a wavelength range extending from 1 cm to just below 1 mm, and power levels of 200-250 kW in the 1 cm range were obtained. In the 1 cm range, voltage-tuning over 1 octave was achieved, and at 3 mm, a single structure was tuned from 88 to 130 Ghz. At the higher power levels, gas breakdown was used

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as a diagnostic tool. This work was described in a number of publications and a bibliography and abstracts are attached.

A flat-grating cylindrical mirror-based device (the relativistic orotron) was also examined. Power levels comparable to or greater than the best that can be obtained from mm-wavelength, coupled-cavity, travelling-wave tubes were obtained. The voltage-tuning range of these devices was also substantial. Single resonators were tuned over a half octave range, about 30 Ghz, and at higher frequencies (60-80 Ghz) $\pm$10 percent tuning was achieved. The peak power at shorter wavelengths was 10 KW, and in the 1 cm range, 30 KW levels were obtained.

The development of the mm-wavelength Cerenkov source also led to consideration of far- to near-infrared Cerenkov lasers. These were compared to the undulator type of Free-Electron lasers, and their relative advantages and disadvantages explored. A proof-of-principle far-infrared experiment has been proposed.

CERENKOV MASER AND CERENKOV LASER DEVICES

Final Report

John E. Walsh

March, 1985

U.S. Army Research Office

DAAG29-83-K-0018

Dartmouth College

Cerenkov Maser and Cerenkov Laser Devices

The work supported by this contract spanned a number of topics. The principal effort was directed toward exploration of Cerenkov maser performance at lower-mm wavelengths. However, this work also led to the consideration of tunable, high-power, submm and far-infrared Cerenkov lasers, and to the more general topic of compact free-electron lasers. In addition, structures other than Cerenkov resonators were examined. Among these were cylindrical and flat-plate gratings (the Relativistic Orotron). Detailed summaries of the work are contained in the four six-month reports (June and December of 1983 and 1984), in doctoral theses, abstracts, and journal publications. A bibliography is attached to this report, and copies of the published work have been forwarded earlier. Hence only a brief review of the principal results will be given here.

Cerenkov masers were operated over the entire mm-wavelength region. At longer wavelengths (5-10 mm), octave tuning and multi-hundred kW output power levels were achieved from a single structure. In the 3-mm-wavelength region, tuning between 90 and 130 GHz from single resonator structures was demonstrated, and power levels in the 100-kW range were obtained.

Operation on higher-order modes and with two-stage structures were also demonstrated. Substantial

(multi-kW) power levels at wavelengths slightly below 1 mm were obtained by operating on the TM_{02} mode of a cylindrical dielectric resonator. There is also some experimental evidence that mode suppression and/or selection techniques can be used to selectively operate on higher-order modes.

The two-stage structures combined a disc-loaded prebuncher and a dielectric resonator - output coupler. The peak output power levels achieved with this configuration were comparable to the single-stage Cerenkov device, but substantially longer output pulses (comparable to the 2 μsec beam pulse) were a characteristic feature of the two-stage system. The possibility of tapering a structure in order to enhance the total efficiency was also considered theoretically.

At the upper end of the observed output power range, breakdown at atmospheric pressure was observed. This effect was used for diagnostic purposes and more recently, controlled experiments on the effect of various contaminants on breakdown threshold have been initiated.

A theoretical program aimed initially at support of the mm-wavelength experiments was also carried out. This work in turn led to a more general consideration of both Cerenkov and grating-based free-electron lasers (C FEL/G FEL). Devices of this type were compared to the undulator FEL, and it was shown that in the far-infrared regime, the C or G FEL would be an attractive competitor in many applications. Preliminary designs for

proof-of-principle experiments were completed, and further experiments are planned.

The principle concern of the initial mm-wavelength experiments was the Cerenkov maser, but early in the work, periodic structures were also used to general radiation. The original purpose of the latter was to develop a source for calibration and comparison, but it has developed into an independent assessment of a device now called the Relativistic Orotron. This work is being carried out in collaboration with a group at the U.S. Army Harry Diamond Laboratories (R. Leavitt, D. Wortmann) and it is based in part on the very successful, low-energy electron-beam-driven orotron experiments performed earlier by that organization. Relativistic orotron tuning curves and output power capabilities were established for a number of resonator-beam combinations. The performance was encouraging. Tuning ranges in excess of that available from the mm-wavelength helix TWT's together with power levels comparable, or well above, that of coupled-cavity TWT's were obtained. A device of this kind could be the basis of a mm-wavelength tube.

In conclusion, the high-power capability and tunability of Cerenkov masers at mm-wavelengths has been demonstrated. The theoretical basis for these devices and for Cerenkov sources at much shorter wavelength has been established, and other attractive tunable source options have been explored.

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Résumé (35-40 mots) / Abstract (35-40 words):

A Čerenkov maser which consists of a mildly relativistic electron beam, a dielectric resonator, and output coupling structures has been operated in the middle to lower mm wavelength range. Experimental and theoretical progress on a submillimeter device will be discussed.

Session(s) / Supp.: Free Electron Oscillators; Gyrotrons

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Cerenkov lasers in the Compton regime

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Abstract

Expressions for operating wavelength, gain, and schematic designs for Compton regime Cerenkov lasers are presented. Conditions required for operation at infrared and visible wavelengths are established and proof of principle experiments are discussed.

Introduction

Cerenkov masers have been operated in the millimeter wavelength region[1,2]. Multi-hundred kilowatt power levels have been obtained in the 7-8 mm range and approximately 100 kW have been achieved at about 3 mm. Less power has also been obtained at wavelengths slightly shorter than 1 mm. The requirements for a Cerenkov device at even shorter wavelengths, where operation in a Compton mode is anticipated, have also been considered previously[3].

The purpose of this work is to specifically address the possibility of operating a Cerenkov laser in the infrared region of the spectrum. An expression for gain applicable in this region is examined in section II and adapted to a thin film configuration in section III. Beam parameters similar to those found in a microtron are then used to evaluate the linear gain in section IV. Conclusions are discussed in section V.

II. Gain of a Cerenkov laser

The gain, in the Compton limit, of a Cerenkov laser has been discussed elsewhere[3,4]. Expressed in terms of an inverse quality factor, Q_b^{-1}, it has the form

$$\frac{1}{Q_b} = \frac{1}{2}\frac{1}{(\beta\gamma)^3}\frac{I_b}{I_o}\frac{\bar{n}}{n_o}\frac{L^3|E_z|^2}{\mathcal{E}}\frac{\partial}{\partial\theta}\left(\frac{1-\cos\theta}{\theta^2}\right) \tag{1}$$

where β and γ are the relative beam velocity and energy, respectively. Other terms appearing in equation (1) are

I_b	-	beam current
I_o	-	$mc^3/e \equiv 17000$ amp
$\bar{n}/n_o$	-	beam density form factor
L	-	resonator length
$\lvert E_z\rvert^2$	-	square of the magnitude of the axial electric field strength at the resonator-vacuum boundary
$\mathcal{E}$	-	energy stored in the entire resonator volume
θ	-	relative transit angle $\equiv (kv - \omega)\, L/v$, where ω, k are the angular frequency and axial wavenumber of the resonator mode.

The magnitude, $|1/Q_b|$, determines the threshold Q required for oscillation and $|1/Q_b|$ times $\omega L/v$ is the relative gain per pass. The beam density form factor is defined by

$$\frac{\bar{n}}{n_o} = \frac{1}{A_b\,|E_z|^2_{surface}}\int_{\substack{\text{BEAM}\\\text{AREA}}} dA\;|E_z(\underline{r}_\perp)|^2 \tag{2}$$

where n_o is the peak density of the beam and A_b is an effective area. When the beam distribution is approximately rectangular and a mode geometry appropriate to a thin dielectric film is assumed, $\bar{n}/n_o$ has the form

$$\frac{\bar{n}}{n_o} = e^{-2qd} \frac{(1 - e^{-2qb})}{(2qb)} \qquad (3)$$

Here, $q\ (=\sqrt{k^2 - \omega^2/c^2})$ is the evanescence rate of the field in the transverse direction, i.e., $E \propto e^{-q|r_\perp|}$, d is the gap between the beam and the dielectric surface, and b is the beam thickness. It is clear that both $\bar{n}/n_o$ and $\frac{L^3 |E_z|^2}{\varepsilon}$ depend on beam energy and the resonator geometry. These will be evaluated for the specific case of a thin film guide.

III. The thin film guide

The wave guiding properties of a thin dielectric layer are well known[5]. Disregarding, for the moment, any variation across the guide in the direction perpendicular to that of propagation, the dispersion relation for a TM mode is given by

$$pa \tan (pa) = \varepsilon qa \qquad (4)$$

where $p = \sqrt{\frac{\omega^2 \varepsilon}{c^2} - k^2}$, q is as defined earlier, and a is the guide thickness. In the wavelength region of interest here, the relation between $\omega a/c$ and ka (determined via Eq. (4)) is roughly linear with a slope approaching that of the dielectric light line, i.e., $c/\sqrt{\varepsilon}$. The lowest order mode has no cutoff wavelengths, while TM_{on} , $n \geq 2$, has a cutoff on the vacuum light line ($q = 0$). As the phase velocity varies from c down to $c/\sqrt{\varepsilon}$, a decreasing fraction of the energy is stored above the surface. This feature will be important when we discuss the energy dependence of $\bar{n}/n_o$.

The thin film guide has been used in a number of recent nonlinear optical experiments where power density levels in the MW/cm^2 range have been generated. We will consider guides designed for this spectral range in our Cerenkov resonators.

As an electron beam propagates near the surface of a dielectric guide, it couples best to TM modes with a phase velocity infinitessimally less than the beam velocity. Hence, it is the region of the dispersion curve around phase velocity synchronism,

$$v = \frac{\omega}{ck} \qquad (5)$$

that is of most interest.

The wavelength at velocity synchronism, plotted as a function of reciprocal beam energy, is displayed for two different guide thicknesses in figures 1a and b:

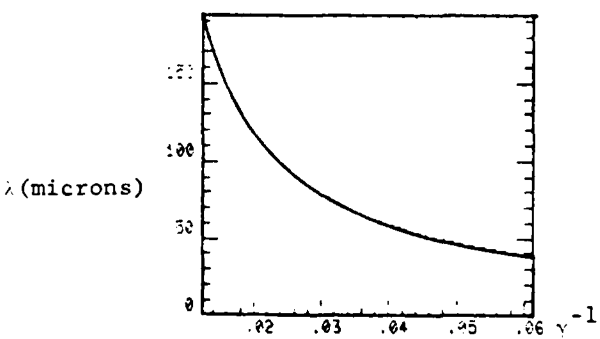

Fig. 1a: Wavelength vs. inverse gamma for 1 micron polystyrene film.

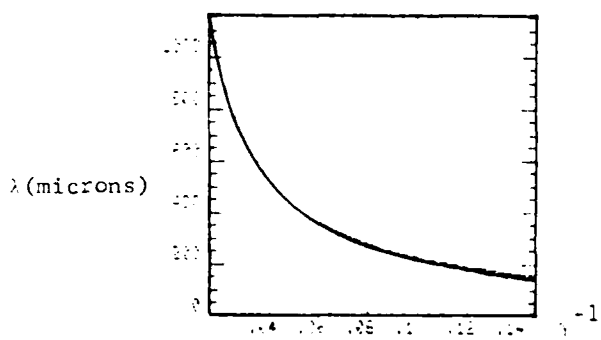

Fig. 1b: Wavelength vs. inverse gamma for 10 micron polystyrene film.

It is clear that coupling in the infrared is possible, in principle.

As the reciprocal of the relative beam energy, γ, varies from 0 (on the light line to $1/\gamma_T$ γ_T is the threshold energy for Cerenkov radiation), the driven mode moves along the dispersion curve. The coupling factor $\bar{n}/n_o$ and the resonator form factor $\frac{L^3 |E_z|^2}{\varepsilon}$ also vary along this curve. These factors are shown in figures 2a and b and 3a and b for the same two guide thicknesses plotted previously. We have assumed, in the $\bar{n}/n_o$ plots, beam

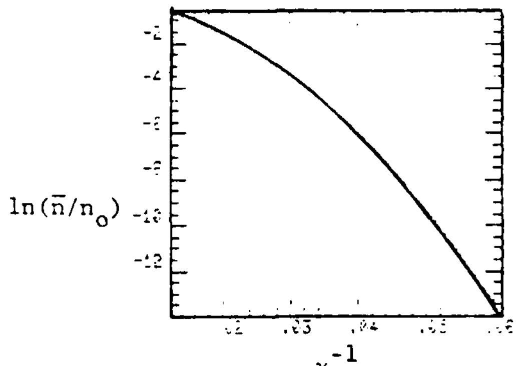

Fig. 2a: Log (beam density factor) vs. inverse gamma for 1 micron film.

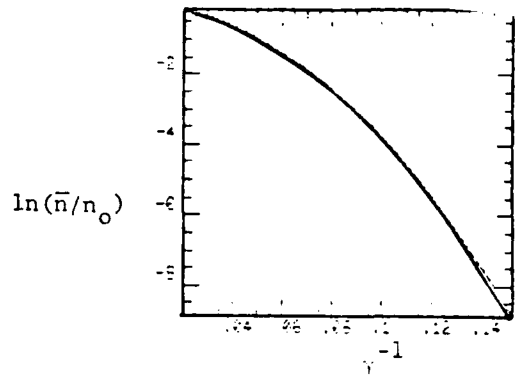

Fig. 2b: Log (beam density factor) vs. inverse gamma for 10 micron film.

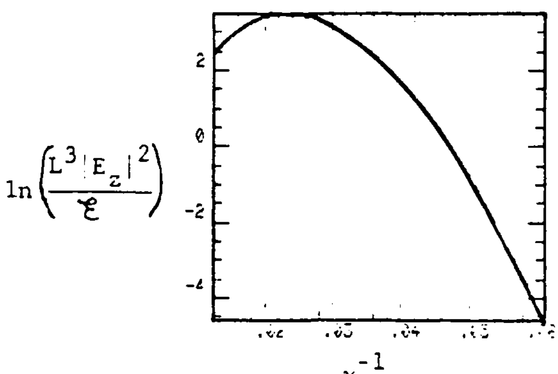

Fig. 3a: Log (resonator form factor) vs. inverse gamma for 1 micron film.

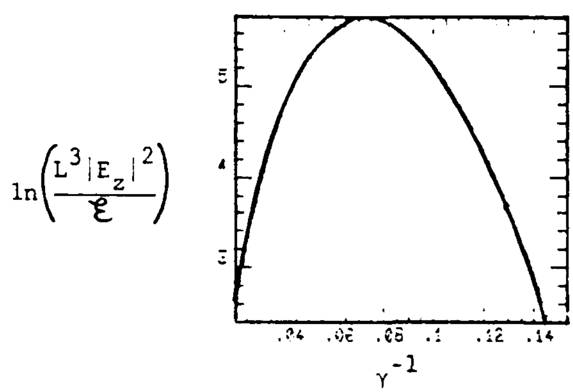

Fig. 3b: Log (resonator form factor) vs. inverse gamma for 10 micron film.

guiding parameters and beam focussing which are favorable but well within the state of the art.

It is clear that the net gain will be determined by design tradeoffs between the rapid decrease of $\bar{n}/n_o$ and the increase of the resonator form factor as the beam energy traverses the dispersion curve from higher toward lower energy.

IV. Cerenkov gain in the infrared.

The complete expression for the gain can now be evaluated. In doing so, we choose beam parameters which apply to two different microtron generators that have been adapted for Wiggler-coupled free electron laser experiments[9]. The relevant parameters are:

I_b = 1 amp

L = 10 cm

θ = θ_{max}

b ≡ beam width = 100 microns

d ≡ beam-film gap = 500 microns

a ≡ film thickness = 1 and 10 microns

ϵ ≡ dielectric constant of film = 1.6 (polystyrene).

Plots of Q_b^{-1} vs. γ^{-1} are shown in figures 4a and b for film thicknesses of 1 and 10 microns. We see that, for the 1 micron film, the gain peaks at about 16 MeV, which corresponds to the 60 to 80 micron wavelength region (see figure 1a). The 10 micron film has a gain peak at about 5 MeV and a corresponding wavelength emission range of 100-200 microns.

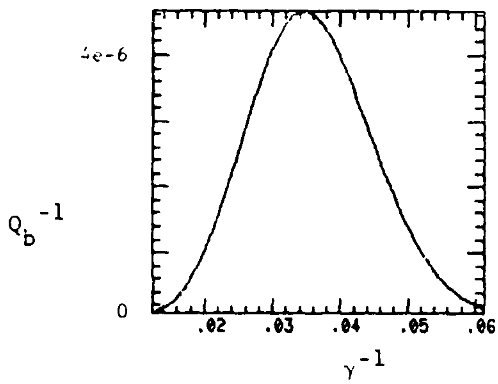

Fig. 4a: Inverse Q vs. inverse gamma for 1 micron film.

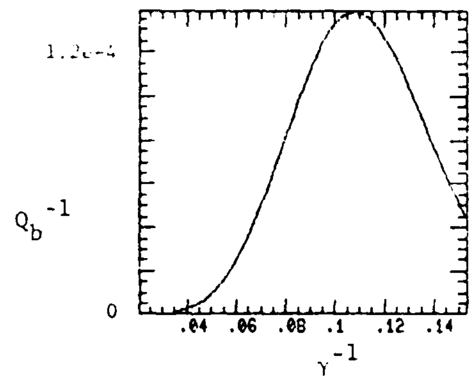

Fig. 4b: Inverse Q vs. inverse gamma for 10 micron film.

V. Conclusions

It seems readily apparent from the foregoing examination that thin film waveguide structures can be used to provide radiation in the infrared region of the spectrum. The thickness of the film and its dielectric constant are the factors which determine the wavelength of the emitted radiation. Beam and resonator parameters determine the net gain of the device. Our analysis, which uses a realistic beam geometry, energy, and film type, yields Q_b^{-1} values well within the range required for oscillation of such a device. Future work in this area will introduce a double-slab geometry as well as an examination of the effect of beam energy spread on net gain.

Acknowledgments

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CERENKOV LASERS

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Abstract

Cerenkov lasers, which are driven by a relativistic electron beam, may be based either upon dielectric waveguide resonators or gas-filled Fabry-Perot resonators. When the beam energy exceeds the Cerenkov threshold, stimulated Cerenkov radiation causes beam bunching, and energy can be extracted at a wavelength determined by the beam and the resonator characteristics. Devices have already been operated successfully in the lower- and submillimeter regime. The possibility of far-infrared operation will be discussed in this paper.

I. Introduction and Background

An electron beam of sufficient energy, a dielectric resonator or waveguide, and suitable output coupling components can be used to form a Cerenkov laser. When the beam velocity is greater than the speed of light in the dielectric medium, spontaneous Cerenkov radiation is emitted.[1] This, when fed back onto the beam, causes further stimulated[2] Cerenkov radiation and, if the feedback is sufficient, the wave energy grows in time.

The dielectric resonator may be a homogeneous medium or some type of dielectric waveguide. In the former case, the only practical material is a gas. This requires a rather large beam energy, i.e. tens of MeV's. These systems have been investigated[3,4] theoretically and some preliminary experimental work has been done. In particular, it has been demonstrated that when a laser is phase-matched to the velocity of an electron beam in a gas, the beam momentum can be modulated.[3]

A dielectric surface guide can also be used to produce the necessary phase velocity decrease and systems based on this approach will be the concern of this paper. Dielectric resonators in tubular form have been used in the mm range to produce a high-power tunable source.[5] Power levels in the 100 KW range at about 3 mm wavelengths have been produced and operation down to wavelengths just below 1 mm has been achieved. In the present paper we will investigate the possibility of achieving a far-infrared source with a slab waveguide resonator.

The remainder of the manuscript is divided into three parts. Section two contains discussions of the guide resonator, the stimulated emission rate, and an estimation of the power output. Examples are presented in section three and some conclusions are discussed in section four.

2. Wavelength Determination and Gain

2.1. The film waveguide

The simplest dielectric waveguide, the slab, is the one chosen for the present application. Discussion of the general behavior of a slab guide is available elsewhere[6] and hence only those features pertinent to the present device need be summarized. A sketch of the cross-section of the guide is shown in Fig. 1 as is the profile of the electric fields of a TM mode. The fields evanesce in the vacuum region with an inverse scale length:

$$q = \sqrt{k^2 - \frac{\omega^2}{c^2}} \qquad (1)$$

where k is the axial wave number and ω is the angular frequency of the bound mode.

Also shown on Fig. 1 is a sketch of the dispersion relation. The latter is determined by the roots of

$$pa \frac{\text{Tan}\, pa}{\varepsilon} = q \qquad (2)$$

where

$$p = \sqrt{\frac{\omega^2 \varepsilon}{c^2} - k^2} \qquad (3)$$

is the transverse wave number in the dielectric medium and ε is the relative dielectric constant. When the wavelength is long compared to the thickness of the guide, the phase velocity of the mode approaches the speed of light. As the wavelength decreases, the wave becomes more tightly bound and the phase velocity asymptotically approaches that of light in the dielectric medium.

A line with slope β is indicated on the dispersion curve. When $\beta > 1/\sqrt{\varepsilon}$ a synchronous phase condition can be maintained between a beam with relative velocity β and a guided mode. If $\beta > \omega/ck$ by a small amount, net energy can be added to the field.

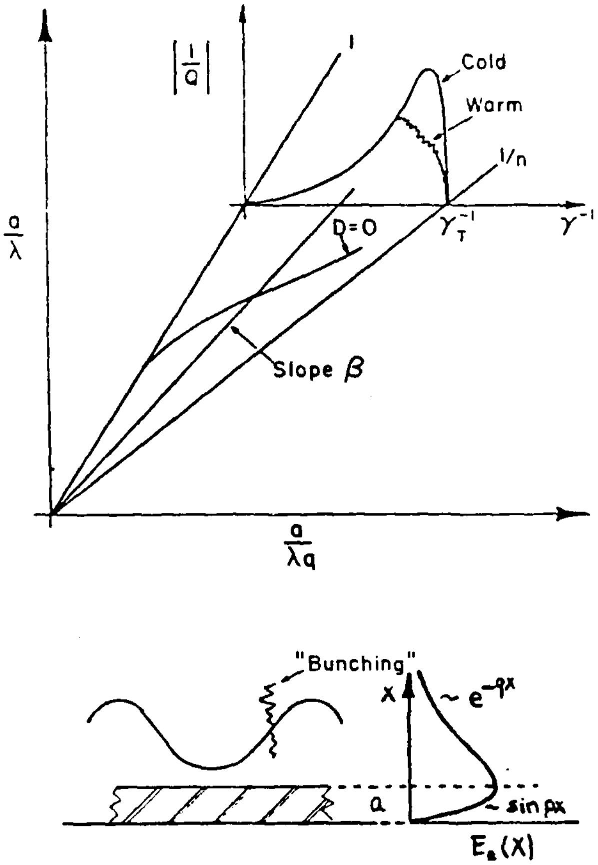

Figure 1: Dispersion relation, Q^{-1} vs. γ^{-1}, guide cross-section, and electric field profile.

Phase velocity synchronism thus determines the operating wavelength and since the dispersion curve is a universal function of the guide thickness a , a suitably small value will lead to operation at the desired wavelength.

The condition of synchronism can also be invoked to better understand the coupling strength. Near synchronism

$$\beta \approx \frac{\omega}{ck} \tag{4}$$

and the vacuum region transverse wavenumber q becomes

$$q = \frac{2\pi}{\lambda\beta\gamma} \tag{5}$$

where λ is the free space wavelength and $\gamma^{-1} = \sqrt{1-\beta^2}$. Thus a high energy beam is needed to achieve reasonable transverse extent of the fields at short wavelengths. This is necessary for good coupling. These features will determine the net gain of the system.

2.2. Stimulated emission and gain.

The stimulated emission rate for a Cerenkov laser follows from the consideration of the work done by an initially unmodulated electron beam as it traverses the length of the resonator. In a general analysis of this problem the dispersion of the beam modes would be considered. However, in the operating region which is anticipated, the plasma frequency of the beam is relatively low and the space charge modes are not resolved from the spectral width associated with the finite length. This so-called Compton regime is familiar in other free electron laser gain calculations.

The rate of work done by the beam is given by:

$$\frac{d\mathcal{E}}{dt} = \frac{-1}{2} \mathcal{Re} \int_{\text{beam}} \underline{j} \cdot \underline{E}^* \, dV \tag{6}$$

The details of the calculation which relate $\underline{j}$, the current density modulation produced by the field $\underline{E}$, and the electric field have been presented elsewhere [7] and hence will not be repeated. A gain is conveniently defined in terms of an inverse quality factor Q_b^{-1}:

$$\frac{1}{Q_b} \equiv - \frac{\omega}{\mathcal{E}} \frac{d\mathcal{E}}{dt} \tag{7}$$

where $\mathcal{E}$ is the energy stored in the resonator. When Q_b is negative and $|Q_b| < Q_L$, the Q of the loaded cavity, the threshold for oscillation is reached.

When placed in a form applicable to the slab guide resonator, Q_b^{-1} may be expressed as:

$$\frac{1}{Q_b} = \frac{1}{(\beta\gamma)^3} \frac{I}{I_o} \frac{\bar{n}}{n_o} \frac{L^3 |E_z|^2}{\mathcal{E}} G'(\theta) \tag{8a}$$

where

$$G'(\theta) = \frac{\partial}{\partial\theta} \left(\frac{1-\cos\theta}{\theta^2} \right) \tag{8b}$$

and

$$\theta = (ck\beta_o - \omega) L/c\beta_o \tag{8c}$$

The angle θ , the transit angle, is related to the relative phase change "seen" by an electron as it traverses the wave in the resonator. Other factors not yet identified which appear in Eq. (8a) are: I, the beam current, a collection of fundamental constants $I_o = mc^3/e$ (17 KA), and an effective beam density $\bar{n}/n_o$. The latter factor takes into account the evanescence of the fields in the direction normal to the resonator surface. It is a sensitive function of both the beam and

the resonator parameters. Also appearing in Eq. (8a) is the term $L^3|E_z|^2/\mathcal{E}$. Here, L is the resonator length in the beam direction and E_z is the strength of the axial component of the electric field at the surface of the resonator. This factor, together with $\bar{n}/n_o$, determines completely the wavelength dependence of the coupling.

The factor $G'(\theta)$ is the derivative of the familiar square aperture diffraction line shape. Its presence may be understood in the following way: Electrons which enter the resonator in an accelerating phase of the electromagnetic field spend less time in the resonator and hence exchange less energy. It is in this way that an initially unmodulated beam can, if its initial velocity has the proper relation to the phase velocity of the mode, do a net positive amount of work on the fields stored in the resonator. Such a factor is familiar in other free electron laser gain expressions and certain microwave tube gain functions.

A qualitative sketch of Q_b^{-1} is included on Fig. 1. When the beam energy is very high ($\beta \to 1$) the gain drops rapidly due to the factor $(\beta\gamma)^{-3}$ and the phase velocity dependence of $L^3|E_z|^2/\mathcal{E}$. The curve rises to a maximum determined by the dispersion relation and then rapidly drops to zero as the beam energy approaches the threshold for Cerenkov emission. If one assumes that the beam is perfectly monoenergetic, the gain peaks quite close to threshold. A finite emittance and/or energy spread will shift the peak toward longer wavelengths and higher beam energies. This effect is illustrated by the jagged line on the Q_b^{-1} diagram in Fig. 1. The gain expressed in terms of a threshold or starting current will be evaluated numerically in section 2.3.

2.3. Gain saturation and output power.

One further aspect of Cerenkov laser operation will be considered before we proceed to some examples. A detailed nonlinear theory of Cerenkov lasers has not yet been completed. However, a reasonable estimate of available power output is possible with the aid of the following rather simple argument.

If $Q_b < 0$ and Q_L (the loaded Q of the cavity) are such that $|Q_b| < Q_L$ then the field energy stored in the cavity will rise exponentially with time at a rate proportional to $(1/|Q_b| - 1/Q_L)$. This process will continue until the axial component of the electric field is large enough to cause a non-neglible change of the electron velocity. At this point, E_z becomes large enough to shift the electron velocity and hence the relative phase change θ from the position of maximum small-signal gain (emission) to a region where it absorbs and the gain will saturate. The general behavior of all traveling wave systems is similar and a more detailed theory could be adapted from some other systems. The above argument will be sufficient for the present estimate.

When the nonlinear phase change becomes of order π the open orbits wind up and the gain saturates. Using the initially linear theory as a starting point, we then have

$$\frac{\omega L}{v^2}\ \delta V \approx \pi \tag{9}$$

where

$$|\delta V| \approx \frac{e}{m\gamma^3}\ \frac{E_z}{(kv-\omega)}\ . \tag{10}$$

It is assumed in this estimate that the net beam energy change is relatively small. Using Eqs. (9) and (10), plus the fact that θ_o is of order $\pi/2$, the estimated axial field strength takes the form:

$$e\ E_z L \ = \ mc^2(\beta\gamma)^3\ \frac{\lambda}{L} \tag{11}$$

The output power, given a value for Q_L, can now almost be estimated. There remains, however, the problem of suitably averaging over entrance phase. An acceptable approximation for this can be adapted from the expression for Q_b^{-1}. The Vlasov approach used in deriving Q_b^{-1} contains an implicit phase average. Hence an approximate expression for power output may be displayed:

$$P_{out} \ = \ \omega\left(\frac{1}{Q_b} - \frac{1}{Q_{bs}}\right)\mathcal{E} \tag{12}$$

where Q_{bs}^{-1} is an assumed threshold gain ($|Q_{bs}^{-1}| \equiv Q_L^{-1}$).

Substituting from the preceding equations and collecting terms, we then have

$$P_{out} = mc^2(\beta\gamma)^3\ \frac{\lambda}{L}\ (\bar{N}_b-\bar{N}_{bs})\ G'(\theta) \tag{13}$$

where $\bar{N}_b$ is the current divided by charge and averaged over the transverse mode distribution. Numerical values appropriate to a far-infrared device will be considered in the next section.

3. An Example

The following example is chosen to illustrate the feasibility of developing far-infrared Cerenkov devices.

It is assumed that a thin film dielectric such as that used in a number of recent experiments is used to support the wave. [8] The dispersion curve for the TM modes of the thin film is a universal function of the film thickness a. Shown in Fig. 2 the dependence of λ/a at velocity synchronism vs. γ^{-1}

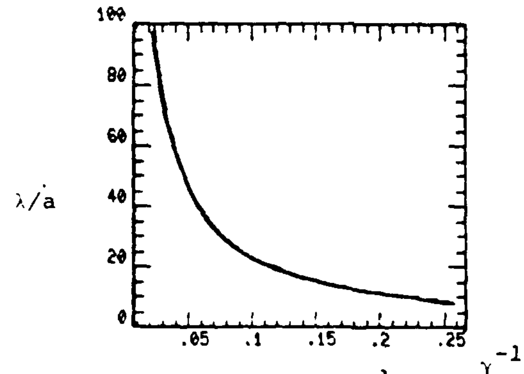

Figure 2: λ/a vs. γ^{-1}

As the energy approaches the Cerenkov threshold energy the λ/a vs γ^{-1} curve becomes very flat since in this region the wave is moving with a velocity very near to that of light in the dielectric. The curve shown is the TM_{01} mode which has no cutoff and hence supports waves with relatively large λ/a. However, when a is in the 1 micron range, λ will be conveniently in the far infrared.

The gain expressions developed in section 2, point two, could now be evaluated for a specific resonator. It is more intuitive, however, to consider the current required to start an oscillation growing. Assuming about ten percent of the wave energy is lost in the guide to various absorbing processes, a threshold Q_T can be established. Setting $1/|Q_b| = 1/Q_T$ and solving for I_b/I_o then determines the starting current I_{bs}. These are plotted in Fig. 3 for three different guide thicknesses, and the following set of beam and resonator parameters:

a) L ≡ resonator length = 10 cm
b) beam width = 100 microns
c) beam-film separation = 100 microns
d) film dielectric constant = 1.6 (polystyrene).

We see that, as the film thickness decreases, the current required to achieve oscillation increases. For example, the minimum start-up current for a 10 micron film is 14 mamp. while that for a .5 micron film is 3.8 amp.

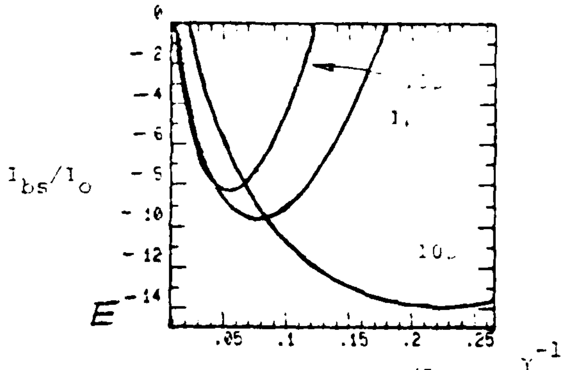

Figure 3: Start-up current/I_o vs. inverse gamma.

Finally, we choose a beam current such that oscillation is readily achieved for all three film thickness, e.g., I = 10 amp. Figure 4 shows the power output vs. inverse gamma as derived in Eq. (13) for the three thicknesses.

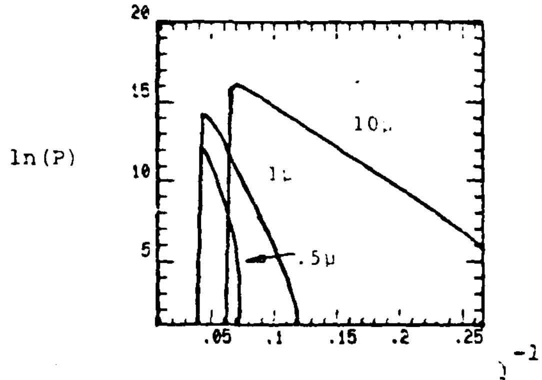

Figure 4: Power (in Watts) vs. γ^{-1}

Substantial power output is possible as evident in the range of peak powers displayed in the above graph, i.e., .15 MWatts for a .5 micron film to 15 MWatts for a 10 micron film.

4. Conclusions

A preliminary investigation into the feasibility of using a slab (film) waveguide resonator and a relativistic electron beam to generate far-infrared radiation yields promising results.

The use of the slab guide dispersion relation enables us to determine the operating wavelength as a function of beam energy. The choice of slab thickness, in turn, identifies the wavelength region of operation, e.g., thicknesses on the order of 1 micron yield radiation in the far infrared.

The linearized Vlasov equation is applied to a cold beam to derive an expression for the stimulated emission rate and, hence, a beam quality factor Q_b. The assumption of a realistic loaded

cavity Q_L value is then used with Q_b to determine the start-up currents necessary to achieve oscillation. The beam energies and currents indicated are not uncommon at existing facilities.

Finally, an expression for power output has been derived which indicates that this is a potentially high power device (MWatts).

Further theoretical work on this subject will involve: 1) a more realistic beam model, i.e., one which includes a finite beam emittance, 2) beam mode dispersion, 3) other resonator geometries, such as a double slab, and 4) the development of a complete nonlinear theory.

In addition, the authors are optimistic that experiments will be performed in the near future to demonstrate the operation of a far-infrared Cerenkov laser.

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Division of Plasma Physics
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Category Number and Subject 4.9 Coherent Radiation Generation
.3 Free Electron Lasers

☐ Theory ☒ XX Experiment

Experimental Performance of a Cerenkov Maser at Lower mm Wavelengths. J. WALSH, E. GARATE, T. BULLER, R.W. LAYMAN, R. COOK and D. WILLEY, Dartmouth College*--Cerenkov Masers have achieved hundred-KW power levels in the middle-mm range and outputs in excess of ten KW in the lower-mm region[1]. Substantial output levels, on higher order cavity modes, have also been obtained at wavelengths below 1 mm. However, the typical single-stage high power output pulse is often considerably less than the electron beam pulse length. In the longer wavelength range, two-stage, oscillator-amplifier operation has been used to increase the pulse length and the overall stability of the output. The results of attempts to extend this concept to shorter wavelength will be discussed. In addition, resonator design criteria for fundamental mode operation in the 1-mm wavelength range and preliminary experimental results will be presented.

1. A High Power Cerenkov Maser Oscillator, S. Von Laven et al., Appl. Phys. Lett. 41(5), 408 (1982).

*Supported in part by AFOSR Contract # 82-0168 and ARO Contract # DAAG29-83-K-0018.

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Recent Cerenkov Maser Experiments

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Abstract

Fundamental (TM_{01}) mode operation at 3 mm, and higher order mode operation at wavelengths below 1 mm, have been obtained in a recent series of Cerenkov maser experiments. Device performance will be compared with theoretical expectations.

A mildly relativistic (100-200 KeV), moderate current (10-20 A) electron beam and a cylindrical waveguide lined with dielectric have been used to produce 50 kW power levels in the 100 GHz region of the spectrum. The device, A Cerenkov Maser, couples the slow space-charge wave on the beam to the TM modes of the guide. The operating wavelength is determined by phase velocity synchronism between the guide mode and the beam velocity. The wavelength at which this occurs is in turn controlled by the guide dimensions, the relative dielectric constant of the filling material, and the fraction of the guide volume that is filled with dielectric.

The beam-to-wave coupling strength is determined by the strength of the axial component of the field in the beam region. When the system is cylindrically symmetric the field is proportional to a modified zero order Bessel function. Good coupling is thus insured if the approximate relation

$$\pi a \simeq \lambda \beta \gamma \qquad (1)$$

is maintained. This last relation follows if it is assumed that the evanescence of the wave in the beam channel causes the field on axis to be equal to one half its value at the channel radius (a). In Equation (1), λ is the free space wavelength, β is the relative beam velocity, and γ the relative beam energy. The relations between the beam, the guide, and the axial field dependence is illustrated in Figure 1. Also shown on this figure is a schematic representation of the dispersion relation for the TM mode of a partially-filled guide and the beam velocity line β. Synchronism of the beam and mode velocities occurs at the intercept of these two curves.

Typical Cerenkov source data is shown in Figure 2. In the first part of the figure, output power at 4 mm vs. beam current and a typical output pulse are displayed. Wavelength has been determined with cutoff filters, a grating

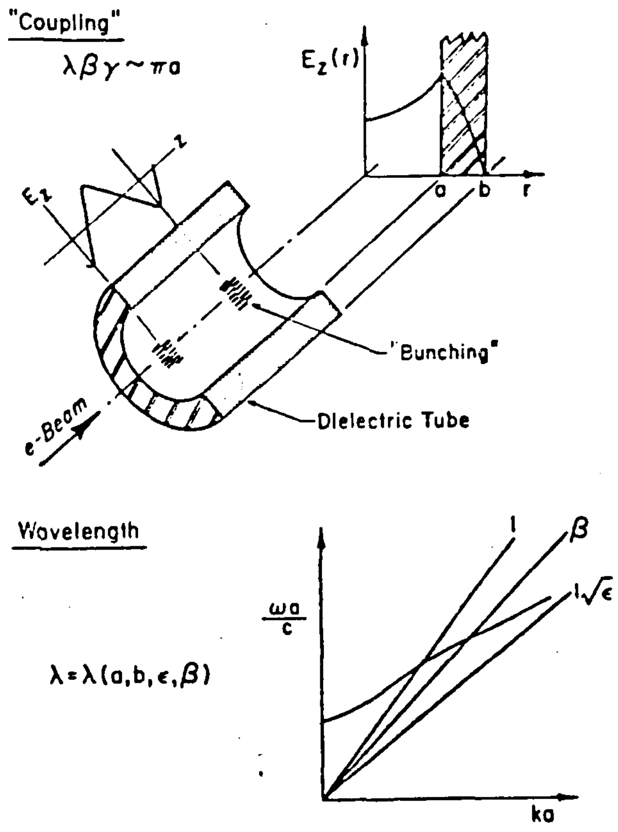

Figure 1. Cerenkov source geometry.

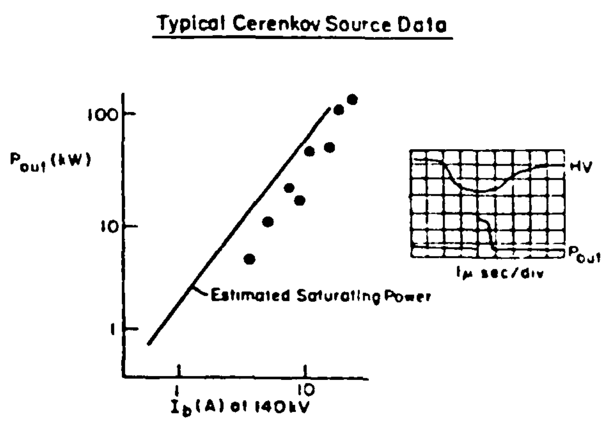

Figure 2a. Power output.

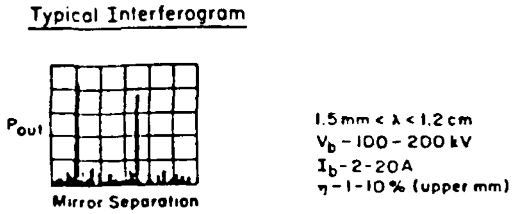

Figure 2b. Interferogram.

spectrometer, and Fabry-Pérot interferometers. Shown on the Figure 2b is a typical interferogram.

Theoretical expressions for the gain, the starting current, and estimated saturating out power of mm wavelength Cerenkov Masers will be presented. In addition, beam and resonator modifications required for operation at submm wavelengths will be discussed.

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SUBMILLIMETER-WAVELENGTH CERENKOV MASERS

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A gas-filled Fabry-Pérot cavity driven by a highly relativistic electron beam could, in principle, act as a Cerenkov laser[1]. However, the practical problems associated with electron beam transport through the dielectric medium would appear to limit this device to the visible - UV region of the spectrum. In the far-infrared - submm region of the spectrum, a source based upon a mildly relativistic electron beam and a thin film dielectric waveguide is an attractive alternative. The thin film dielectric guide is by no means the only slow wave structure that could be used in this spectral region but, as the operating wavelength of a source is decreased, it has some advantages over periodic structures. Two of these advantages which should be noted here are the relative ease of fabrication, and the fact that the device operates on a single spatial mode. The latter feature means that the beam-to-guide mode coupling strength for a dielectric guide-based resonator can exceed that of a similar sized periodic structure-based system.

The general features of stimulated Cerenkov radiation have been discussed in a number of places[2,3]. In this summary we will concentrate on devices which are designed to operate in the submm region of the spectrum. A dielectric surface guide will support slow TM modes which can be phase-velocity-matched to an electron beam propagating parallel to the surface of the guide. When the beam velocity slightly exceeds the phase velocity of the mode, electrons will bunch in the retarding phase of the axial component of the field and beam energy will be given up to the wave.

The wavelength at which this exchange occurs is determined by the dispersion relation for the mode, and this is in turn determined by the film thickness and its relative dielectric constant. A suitable film thickness (5-50 μ), which has a moderately low relative dielectric constant ($\varepsilon \sim 2.2$), will support modes in the far-infrared - submm region of the spectrum.

A second important design consideration is the scale length of the evanescence of the slow wave. This is approximately exponential and has an inverse scale length equal to the product $2\pi/\lambda\beta\gamma$ where λ is the wavelength, β is the relative beam velocity and γ the relative beam energy. Thus, if λ is varied between 0.5 and 1 mm, beam energies between one and five MeV imply a convenient transverse dimension (several mm for a symmetrical structure).

The following quantitative expression[4] for the gain has been derived under the assumption that beam space charge modes are unimportant. If this is not the case, the theory can be modified[2,3], but the so-called collective limit will not apply to the devices considered herein. The energy exchange occurs in the following way: An initially unmodulated beam enters a thin film dielectric resonator cavity and has modulation impressed upon it at the wavelength of the electric fields in the resonator. This current in turn either adds of subtracts energy from the resonator. The net exchange rate is given by Poynting's theorem:

$$\frac{d\mathcal{E}}{dt} = -\frac{1}{2} R_e \int \underline{j} \cdot \underline{E} \, dV \tag{1}$$

where $\underline{j}$ is the modulated current on the beam. It is convenient to express this gain as a reciprocal quality factor Q_b^{-1} :

$$\frac{1}{Q_b} \equiv -\frac{1}{\omega\mathcal{E}} \frac{d\mathcal{E}}{dt} \tag{2}$$

where ω is the angular frequency of the radiation and $\mathcal{E}$ is the energy stored in the cavity. A detailed solution of the problem then yields for Q_b^{-1}

$$\frac{1}{Q_b} = \frac{1}{2} \frac{1}{(\beta\gamma)^3} \frac{I_b}{I_o} \frac{L^3}{A_b} \int \frac{dAn|E_z|^2}{n_o\mathcal{E}} \Gamma'(\theta) \tag{3}$$

Terms not yet identified are, I_b, the beam current, $I_o = e/mc^2$ (= 17 KA), L , the cavity length, A_b, the beam area, and n_o, the peak beam density. The factors inside the integral sign determine the beam-to-resonator coupling strength. It is in essence the overlap of the beam density n and the axial component of the electric field. The final term appearing in the gain expression:

$$\Gamma'(\theta) = \frac{\partial}{\partial\theta} \frac{1-\cos\theta}{\theta^2} \tag{4a}$$

$$\theta = (kv_o - \omega) \frac{L}{v_o} \tag{4b}$$

is the gain line shape expressed in terms of the unperturbed transit angle θ . The gain is positive when $Q_b^{-1} < 0$ and peaks in the vicinity of $\theta \approx \pi$. When the beam parameters mentioned above are used to evaluate Eq. (3), start oscillation currents in the 0.1 to 1 A range are a realistic prospect.

Non-linear analysis[5] of the saturation indicates that electronic efficiencies in the one to ten percent range are possible, and hence the above devices should be capable of producing high levels of pulsed power in the submm region of the spectrum.

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Far-Infrared Cerenkov Masers

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A relativistic electron-beam-driven, thin-film, dielectric resonator can be used to produce coherent radiation in the far-infrared region of the spectrum. Design parameters for a device which operates at a wavelength of approximately 100 microns will be presented.

The Cerenkov FEL Mechanism

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In a Cerenkov Free Electron Laser an electron beam becomes bunched in the retarding phase of the axial component of an electromagnetic wave and the bunching is in turn made possible by the fact that the beam is moving with a velocity which is slightly greater than the phase velocity of the wave. This situation can be obtained when an electron beam moves with greater than light velocity either in or near to a dielectric medium. The latter case is more practical when operation with a moderately relativistic beam is desired and the discussion will be confined to this configuration.

A thin dielectric film on a metal substrate will support (TM) modes with the required axial field component. The wavelength at which these modes have a given phase velocity is controlled by the thickness of the film and the index of refraction of the film material, and hence there is a relation between electron beam energy and the wavelength near velocity synchronism. This result may be expressed quantitatively by the approximate scaling relation

$$\text{[illegible]} \simeq 2\text{[illegible]}d\,\text{[illegible]}/\text{[illegible]}_T^{2}$$

where d is the film thickness, [illegible] is the relative beam

energy, and γ_T is the beam energy at Cerenkov threshold ($\gamma_T{}^2 = \varepsilon/\varepsilon - 1$).

The field strength (in the vacuum region) of a wave slowed by a thin film will evanesce with distance away from the film. Assuming that the wavelength near velocity synchronism is the one of interest, the scale length for the evanescence is conveniently expressed in the units $\lambda\beta\gamma$, or since $\beta \sim 1$ in the anticipated operating regime, by the product $\lambda\gamma$.

The relative small signal gain of a Cerenkov laser is obtained by computing the work done by the current induced on the beam by fields in the resonator. This quantity will generally increase with decreasing wavelength until a number of the order of 4π times the gap between a beam and a dielectric film becomes approximately equal to $\lambda\gamma$. When the wavelength is further decreased, the gain drops exponentially.

A Cerenkov laser proof of principle experiment designed for operation in the 100 μm wavelength range and driven by a 5 MeV microtron accelerator is planned. The resonator will consist of two opposing plates terminated with cylindrical mirrors. Within the beam interaction region the plates will be loaded with thin dielectric films. The overall structure supports cylindrical Hermite-Gaussian modes which, within the interaction region, have an axial field component. The details, the gain calculation, the beam homogeneity

requirements, and the anticipated characteristics of the Cerenkov laser will be discussed. It will be shown that the projected operating characteristics of the ENEA-Frascati 5 MeV microtron are well matched to the Cerenkov Laser.

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A Cerenkov Infrared Laser

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USA

Successful production of microwave radiation by Cerenkov masers has prompted an investigation into their feasibility for submillimeter and far infrared wavelength generation. A theoretical examination of output parameters such as frequency and small signal gain has been conducted for an easily fabricated resonator geometry. The resonator consists of two parallel plates, each with a thin (.5 to 3 micron) dielectric coating, seperated by 2 mm. This waveguide will support TM modes which are coupled to a relativistic electron beam propagating between the plates. While the interaction of the electrons with the dielectric causes spontaneous Cerenkov emission, the difference between the beam velocity and the phase velocity of the mode causes a bunching of the electrons which is responsible for further stimulated emission. The frequency of the generated radiation is determined by the dispersion relation of the waveguide mode. Gain is calculated assuming the effects of space charge modes are negligible, i.e., operation in is in the Compton regime. Our results indicate that such a 'double-slab' resonator will provide detectable levels of infrared radiation from a mildly relativistic (3-10 MeV) electron beam.

The theoretical analysis is undertaken in preparation for a series of experiments to be conducted at the ENEA facility in Frascati, Italy, where a 5 MeV microtron accelerator will be used to produce radiation in the 10 to 100 micron range. A suitable choice for the dielectric material would be polyethylene, both because of its low dielectric constant (2.2) and its relatively low loss in the infrared. A detailed discussion of the design choices will be presented.

Undulator and Čerenkov Free-Electron Lasers: A Preliminary Comparison

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(Received 14 May 1984)

A preliminary comparison of the fundamental characteristics of undulator and Čerenkov free-electron lasers is presented. It is assumed that both devices are operating in the Compton regime and that they are driven by a short-pulse relativistic electron beam.

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The purpose of this work is to compare general characteristics of undulator[1] and Čerenkov[2] free-electron lasers (FEL). The former class of device has been operated over a wavelength span which covers the millimeter through visible regions, while, to date, the latter has been primarily used as a near-millimeter–wavelength source.[3] Furthermore, there exists a very detailed[4–7] body of theory covering many aspects of undulator FEL's. However, operation of Čerenkov devices at far-infrared wavelengths has been discussed only briefly. The purpose of this note is thus to compare the gain, the beam energy, and the beam quality requirements of a Čerenkov FEL to those of an undulator-based source.

Highly simplified versions of the two devices are shown in Fig. 1. In Fig. 1(a), a relativistic electron beam moves along the axis of the magnetic undulator and produces radiation at the characteristic wavelength

$$\lambda = \lambda_p(1+\kappa^2)/2\gamma^2, \tag{1}$$

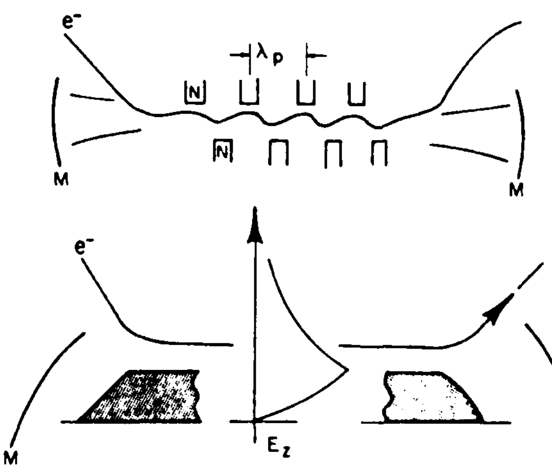

FIG. 1. Schematic form of two free electron lasers. (a) undulator form; (b) Čerenkov form.

where λ_p is the wavelength of the undulator, $\kappa = e\times\lambda_p\bar{B}_p/mc^2$ is the undulator parameter, $\bar{B}_p$ is the pump magnetic field strength, and γmc^2 is the beam energy. Stimulated emission causes bunching and the addition of mirrors forms an oscillator.

In Fig. 1(b), an electron beam moves near and parallel to the surface of a thin-film dielectric waveguide. The beam couples to the axial component of a transverse-magnetic mode of the guide and thereby emits spontaneous Čerenkov radiation in the bounded structure. Again, with the addition of mirrors, it is possible to form an oscillator. The characteristic wavelength of the emitted radiation is determined by a velocity synchronism of the beam and the guided mode. This condition is illustrated schematically in Fig. 2. The exact dispersion curve

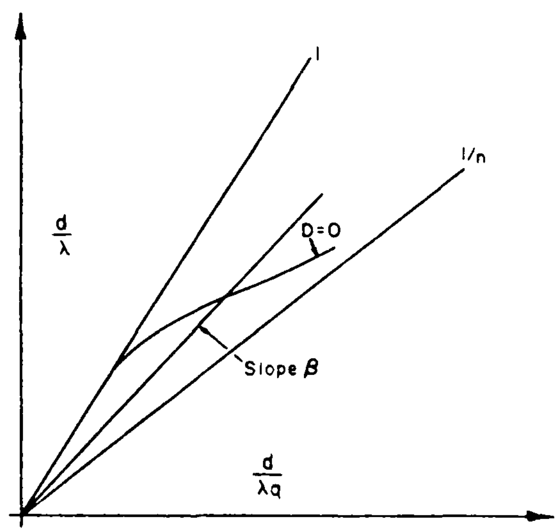

FIG. 2. Typical dispersion curve (inverse wavelength λ vs inverse guide wavelength λ_g) and beam velocity line for a thin-film guide (n is index of refraction of the film material, d is film thickness). The curve D represents the solution to Eq. (2) and β is line with slope v/c.

for a mode with a transverse extent which is considerably larger than a wavelength is given by the well known expression[8]

$$pd\,\tan pd = q\epsilon d, \tag{2}$$

where $p=(\omega^2\epsilon/c^2-k^2)^{1/2}$, $q=(k^2-\omega^2/c^2)^{1/2}$, k is the guide wavelength, ϵ is the relative dielectric constant of the film material, and d is its thickness.

Discussion will be facilitated if we also introduce an approximate solution of Eq. (2), which is

$$\lambda \simeq 2\pi d\gamma/\gamma_T^2, \tag{3}$$

where $\gamma_T^2=\epsilon/(\epsilon-1)$ is the relative energy at Čerenkov threshold. Equation (3) yields wavelengths which are extremely close to the exact solution when $\gamma >> \gamma_T$ and d is small compared to the beam thickness.

The comparative wavelength-energy curves for the two devices are shown in Fig. 3. They are quite distinct. The wavelength of the Čerenkov laser decreases with decreasing energy and depends linearly on the film thickness which can be small. It also varies inversely with γ_T^2 and hence lower ϵ implies shorter wavelength. The wavelength produced by the undulator decreases as γ^2 increases and it depends linearly on λ_p. Pump strength requirements ($\kappa \simeq 1$) generally fix λ_p in the 2–5 cm range. When $d \simeq 3$ μm, $\epsilon \simeq 2$, $\kappa \simeq 1$, and $\lambda_p = 2.5$ cm, the wavelength-energy curves cross in the vicinity of $\lambda = 140$ μm and $\gamma = 14$. The crossover point can be moved about by varying parameters, but these results are typical. Thus, provided other conditions tions can be met, a Čerenkov device has a potential advantage if both short wavelength and lower relative operating electron-beam energies are desired.

The small-signal gain per pass in the resonator of a Čerenkov device is given by the general expression[2]

$$g_0 = \frac{1}{2}\frac{1}{(\gamma)^3}\frac{I}{I_0}\frac{L^2}{A_b}\int\frac{dA\,|E_z|^2}{\mathcal{E}/L}\Gamma(\theta), \tag{4}$$

where I/I_0 is the beam current measured in units of $I_0 = ec/r_0$ ($r_0 = e^2/mc^2$), L is the length of the coupling region, and A_b is the beam area. The integral is done over the beam volume and the symbols E_z and $\mathcal{E}$ are, respectively, the axial component of the electric field and the stored energy in the resonator. The gain line shape is determined by

$$\Gamma(\theta) = \frac{\partial}{\partial\theta}\left(\frac{1-\cos\theta}{\theta^2}\right), \tag{5}$$

where $\theta = (kv_0-\omega)L/v_0$ is the relative phase angle change experienced by an electron moving with initial velocity v_0.

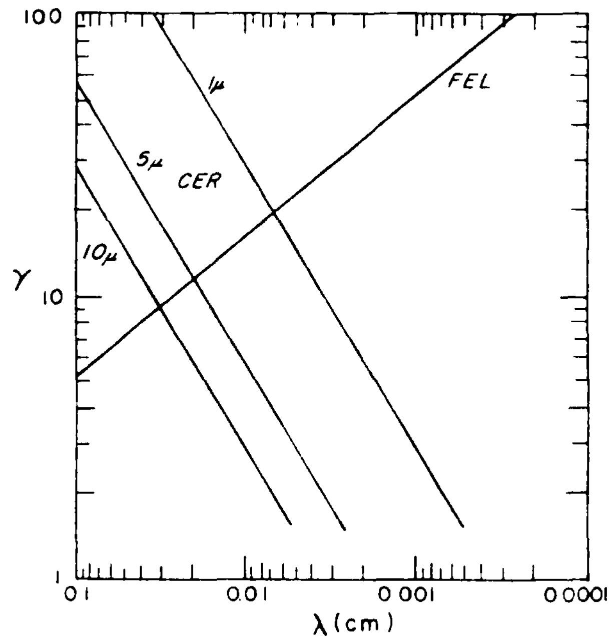

FIG. 3. Comparison of energy wavelength relations for a Čerenkov and an undulator FEL. Three film thicknesses—1, 5, 10 μm—are shown.

When evaluated at the phase-velocity–beam-velocity synchronism and at the maximum of $\Gamma(\theta)$, the general expression is accurately represented by

$$g_0^{(C)} = \frac{2\pi}{\lambda}\frac{L^3}{\sigma_x\sigma_y}\frac{I}{I_0}\frac{e^{-\alpha_0}}{\gamma^5}, \tag{6}$$

where σ_x and σ_y are the beam dimensions in the x and y directions, and

$$\alpha_0 = 4\pi\delta/\lambda\beta\gamma \tag{7}$$

is determined by the gap δ between the beam and the dielectric (β = the relative velocity v/c).

The gain of an undulator-based FEL is given by

$$g_0^{(u)} = \frac{2\pi}{\lambda_p}\frac{L^3}{\sigma_x\sigma_y}\frac{\kappa^2}{(1+\kappa^2)^{3/2}}\left(\frac{2\lambda}{\lambda_p}\right)^{3/2}\frac{I}{I_0}. \tag{8}$$

If it is also assumed for the purposes of comparison that L, σ_x, σ_y, and I/I_0 are the same, and that $\kappa \simeq 1$, the comparative magnitude and the general behavior of $g_0^{(C)}$ and $g_0^{(u)}$ can be displayed (Fig. 4).

Clearly, if λ and γ are also the same for the two devices and α_0 is not large, the gains will be comparable. In general, the gain of a Čerenkov laser will rise with decreasing wavelength, reach a maximum near $\alpha_0 = 1$, and then rapidly decrease as λ becomes still smaller. The value of the wavelength, $\lambda = \lambda_m$, at $g^{(C)}$ = max, is determined by

$$\lambda_m = 4\pi\delta/\gamma. \tag{9}$$

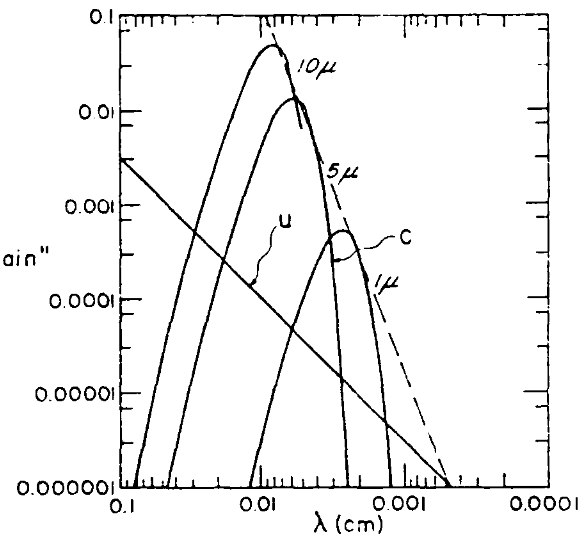

FIG. 4. Comparison of $g_0^{(C)}(\lambda^{-1})$ with $g_0^{(u)}(\lambda^{-1})$. The common factors are suppressed.

Assuming, as is the case in microwave tubes, that δ can be maintained in the 10 to 100 μm range (over a length of ten or twenty centimeters), and that γ ranges between 2 and 20, λ_m will occur in the far-infrared region of the spectrum.

In obtaining the results displayed in Fig. 4, the wavelength variation of the undulator FEL is obtained by varying γ and the curve shows the characteristic $\lambda^{-3/2}$ dependence. In the case of the Čerenkov laser, the film and beam thickness are chosen and the gap is fixed at 50 μm. The device is then tuned along the dispersion curve by again varying γ. The gain at the Čerenkov laser exceeds the undulator laser in those regions where it achieves a given λ at a smaller γ. Furthermore, since the wavelength and the film thickness are proportional, the energy dependence of the gain insures that at longer wavelength the peak $g^{(C)}$ can always be made larger than $g^{(u)}$. Examination of the approximate equation, however, also shows that

$$g_{\max}^{(C)} \sim \lambda^4 , \tag{10}$$

and hence also that there exists some wavelength for which $g^{(u)} > g_{\max}^{(C)}$. With the parameter choices in Fig. 4, this occurs near $\lambda = 1$ μm. The envelope of $g_{\max}^{(C)}$ is shown as a dashed line in Fig. 4.

It is also important to consider the relative efficiency of the two sources. The gain line shape is the same for both and hence in either case, consideration of the field strength needed to cause electron trapping yields an expression for efficiency which is proportional to $\gamma^2\lambda/L$. The Čerenkov laser will operate at a given λ with a lower value of γ and thus would tend to have a lower efficiency. However, $g_0^{(C)} > g_0^{(f)}$ in this region, and therefore L can be made smaller, and thus a part of the difference of η can be recovered.

The gain expressions used assume that the beam is perfectly collimated and hence another important point of comparison is a consideration of the effect of beam inhomogeneities on gain. The principal inhomogeneities listed in Table I have been defined previously.[4] The effects of angular spread and energy spread will have the same form for either laser. The parameters $\mu_{x,y,\epsilon}$ are dimensionless measures of relative dephasing due to angular divergence in the transverse directions or energy spread. When these parameters exceed unity, the beamwidth in frequency space is larger than the gain linewidth and the gain is reduced.

It is anticipated that a Čerenkov laser could be operated with a short-pulse rf-accelerated electron beam, and hence the relative slippage or "lethargy" may also play a significant role. In an undulator FEL the optical pulse slips forward,[4] while in the Čerenkov laser, it slips back. The exact expression for the lethargy of the Čerenkov laser depends on the relative size of the group velocity and the phase velocity. If, however, the operating wavelength is

TABLE I. Beam homogeneity parameters. σ_E is the relative energy spread, $\epsilon_{x,y}$ is the relative emittance (mm · mrad), and σ_z is beam pulse length.

Inhomogeneity parameter	Čerenkov	Undulator
μ_ϵ	$2L\sigma_E/\gamma^2\lambda$	Same
$\mu_{x,y}$	$\sqrt{2}L\epsilon_{x,y}^2/4\pi^2\lambda\sigma_{x,y}^2$	Same
μ_z	$(L/\sigma_z)(1-\beta_g/\beta_0)$	$\lambda_p N/2\gamma^2\sigma_z$

very much smaller than the length of the beam pulse, the gain is relatively unaffected by this slippage. This is the anticipated operating range, and thus a detailed examination of this effect can be deferred.

In conclusion, although many practical details must be examined, a Čerenkov laser is a promising, moderately compact, far-infrared source. The beam intensity and quality parameters (Table I) required for operation in the 50–500 μm range are within the capability[4] of a small (1–5 MeV) microtron accelerator. Support of U.S. Army Research Office through Grant No. DAAG29-83-K-0018 is acknowledged. We would also like to acknowledge the suggestions of U. Bizzarri, W. B. Colson, T. Letardi, A. Marino, and A. Vignati.

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Abstract Submitted
For the Twenty-Sixth Annual Meeting
Division of Plasma Physics
October 29 to November 2, 1984

Category Number and Subject 4.9.2 Coherent Radiation Generation Quasi Optical Systems

☐ Theory ☒ Experiment

A Relativistic Oratron T. Fuller, R.W. Layman, J.E. Walsh Dartmouth College*, R. Leavitt and D. Wortman Harry Diamond Laboratories -- A mildly relativistic, 50-200KV, 1-10A 1 μs long electron beam pulse has been used to drive a variety of periodic structures. A single cylindrical grooved guide with no reflecting structure beyond the mismatch inherent in the grooved to smooth guide transition has been tuned between 40 and 60 Ghz. Flat grating structures which are terminated with cylindrical mirrors have been operated between 50 and 100 Ghz. This latter structure will support modes which are Hermite-Gaussian in the transverse direction. A discussion of experimental details and a comparison of performance with theoretical expectations will be presented.

*Supported in part by ARO contract # DAAG29-83-K-0018 and by HDL-DAAK21-84-Q-T063.

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Abstract Submitted
For the Twenty-Sixth Annual Meeting
Division of Plasma Physics
October 29 to November 2, 1984

Category Number and Subject 4.9.3. Free Electron Lasers

☐ Theory ☒ Experiment

CW Cerenkov FEL, R.W. Layman, J.E. Walsh, Dartmouth College*, J. Silverstein, Harry Diamond Laboratories.--Output power levels of tens of KW in the middle part of the millimeter wavelength range can be obtained from stimulated Cerenkov sources[1]. In these experiments, electron beam pulses 1 μsec long, with 10-20 A of current, at voltages in the 100-200 KV range were used to drive a dielectric resonator. Long pulse and/or CW operation of such a source would be of interest, and in order to examine the potential of such a device a long-pulse, low-current beam generator is under construction. It will operate at voltages ranging up to 250 KV and will typically have a current capability of 100-500 mA. The thermionically-produced beam will be guided and compressed by a combination of electrostatic and magnetic focussing elements. Details of the resonator design, and theoretical expressions for threshold current and Cerenkov gain will be compared for a number of possible resonators. Results of resonator cold-testing will be presented.

*Work supported by ARO Contract # DAAG29-83-K-0018 and HDL Contract # DAAK21-84-Q-8784.

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Abstract Submitted
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October 29 to November 2, 1984

Category Number and Subject 4.9.3 Free Electron Lasers

☒ Theory ☐ Experiment

Infrared Cerenkov Lasers. Bernadette Johnson and John Walsh, Dartmouth College*--Cerenkov lasers, which are successful producers of microwave radiation, have been examined as possible infrared sources. A theoretical analysis of output parameters such as frequency, gain, and power has been conducted for an easily fabricated 'double slab' resonator.

The resonator consists of two parallel plates, each with a thin (5 - 50μ) dielectric coating, approximately 2 to 5 mm apart. This waveguide will support TM modes which are coupled to a relativistic electron beam propagating between the plates. Our results indicate that such a resonator will provide easily detected levels of infrared radiation from a mildly relativistic (3 - 10 MeV) electron beam.

An experiment will be conducted at the ENEA facility in Frascati, Italy using a 5 MeV microtron to produce radiation at about 100 μ.

* This work has been supported in part by U.S.A.R.O. contract #DAAG29-83-K-0018.

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Metal-Grating Far-Infrared Free-Electron Lasers

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Abstract

The general characteristics of grating-based free-electron lasers are established and the beam and resonator parameters needed for operation at far-infrared wavelengths are discussed.

* Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative.

** Tecnologie Intersettoriali di Base.

Čerenkov Maser Operation at Lower-MM Wavelengths

* * *

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* * *

August 1984

Abstract

The basic operating principles of Čerenkov Maser oscillators are briefly reviewed and the experimental performance of a 3-mm device is discussed. A power level of approximately 100 KW was achieved at 88 GHz and voltage-tuning from 84 GHz to 128 GHz on the fundamental TM_{01} mode was observed. Operation on higher-order modes at frequencies up to 300-320 GHz was demonstrated, and a two-stage buncher-amplifier configuration was investigated.

The Cerenkov Maser at Millimeter Wavelengths*

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Abstract

The dispersion relation for the transverse magnetic modes (TM_{on}) of a partially-filled, dielectric-lined, cylindrical waveguide driven by a cold, relativistic electron beam is derived. The effect of a gap between the electron beam and the dielectric liner is included. The dispersion relation is then used to calculate the growth rate for the Cerenkov instability in the collective, tenuous beam limit. Expressions are developed for the minimum current necessary for oscillation threshold and for the power output of the Cerenkov maser in the collective regime.

COMMENTS ON FEL OPERATION WITH OPTICAL UNDULATORS

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Abstract

The possibility of realizing free electron lasers which operate with undulators provided by a real electromagnetic wave are considered. The requirements on the electron beam characteristics needed for a successful operation are defined.

FURTHER COMPARISON BETWEEN CERENKOV AND UNDULATOR FEL DEVICES

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Abstract

In this note, we further analyze the performances of of a Cerenkov-based FEL device and show that, at low energy, they may be better than a conventional undulator FEL.

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Transition Between the Compton and the Collective Limits in a Cerekov Free Electron Laser

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Hanover, NH

The gain of a Cerenkov laser depends upon the coupling between the axial component of an electromagnetic wave and a co-directed electron beam. If the beam velocity is near but slightly greater than the phase velocity of the wave, the electron beam becomes bunched in the retarding phase of the wave and a net energy exchange occurs. In a Cerenkov laser, these conditions are obtained at short (far-infrared or less) wavelengths through a slowing of the wave by a thin dielectric film.

When viewed as a function of beam current density, this interaction has two distinct regimes. In the first, the reaction of beam on the energy stored in the Cerenkov resonator may be ignored for time scales equal to or less than the electron transit time through the resonator. This is the Compton limit. As beam current density increases, however, this approximation will no longer apply and the wave frequency and/or axial wave number must be determined self-consistently from a dispersion relation. In this limit the interaction may be described as collective, since the beam space charge modes may no longer be ignored. These operating regimes, although quite different in some respects, are quite closely related in others.

The gain in the first limit is linearly proportional to current density and in the second to the cube root of this quantity. If, in the first limit, a temporal rate of gain is defined as the gain per pass divided by the transit time, it can be shown that this quantity is proportional to the cube of the collective limit temporal gain rate, times the square of the beam electron transit time. This result, which follows from separate calculations of the gain in the respective limits, is implicitly self-consistent. Once established in this way, however, the result gives a simple means of relating gain in one limiting regime to the gain in the other.

Furthermore, although established in detail for the Cerenkov laser, the result is general. The cube root dependence of the gain in the collective limit follows from the fact that three coupled waves (two space charge and one electromagnetic) take part in the interaction. If the number of modes that are coupled in the collective limit of some device is known, the relation between the collective and Compton gain limits may be specified.

A detailed summary of this result as it applies to far-infrared Cerenkov lasers will be presented and a brief comparison with magnetic undulator free electron lasers will be made.

Support of U.S. Army Contract # DAAG29-83-K-0018 is acknowledged.

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